HYDROLOGICAL CONDITION LEADING TO LANDSLIDE INITIATION

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Abstract
The development of a physically based warning system for rainfall-induced landslides requires a comprehensive understanding of the hydrological condition leading to landslide initiation. The objectives of this research were to evaluate and document the hydrological response of a potential landslide area to heavy rainfall and to assess the significance of the antecedent soil moisture condition to landslide initiation in volcanic residual soils. A field site in an area of previously landslide activity was instrumented and monitored during rainfall period using a number of jet-fill tensiometers. Field monitoring of pore-water pressures indicated that the hydrological response of the soils was spatially and temporally varied in depth. Generally, pore-water pressures within the slopes decrease as the depth increases. At the greater depth, a preferential path for moisture movement may exist to contribute the generation of pore-water pressures. Based on this field measurement, the numerical analyses show that dry antecedent soil moisture condition will require rainfall of high intensity to saturate the soil profile and to disturb the stability of the slope. Under wet antecedent soil moisture condition, rainfall of 80 mm/day is likely to produce the hydrologic condition leading to landslide initiation.

Keywords *landside, pore water pressure, rainfall, tensiometer.*

INTRODUCTION

In tropical countries, like Indonesia, volcanic residual soils frequently exist in an unsaturated state since the residual soils area commonly situated well above the groundwater table. The unsaturated nature of the residual soils lends to their susceptibility to rainfall induced slope failures.

Rainfall-induced slope failures have affected human lives and properties in Indonesia. The slope failures occur almost in all provinces, and cause US$ 1-2 million in damages and more than 20 fatalities on average every year. High occurrence of rainfall-induced slope failures can be attributed in part to the lack of understanding of the mechanism of such slope failures. As such, it is difficult to practice an effective measure to mitigate the hazard posed by rainfall-induced slope failures.

Understanding of mechanisms and conditions leading to the initiation of rainfall-induced slope failures has been generally gained from field measurements and laboratory strength tests. From the results of field measurements, it is generally accepted that the rapid rise of rainfall-induced pore-water pressure is critical to the initiation of slope failures (Johnson and Sitar, 1990). It is typically observed that significant build up in positive pressure heads is generated in an area low on the slope (Sitar and Anderson, 1992; Anderson and Thallapally, 1996). In Singapore and other tropical countries, the effect of reduction in soil suction on soil shear strength has been accounted for in explaining the mechanism of rainfall-induced slope failure in residual granite soil slopes (Rahardjo, 1999); however, the mechanism of pore-pressure generation differs from site to site depending on the site hydrology and soil properties (Sitar and Anderson, 1992, Tohari et al, 2004). The nature of the hydrological response appeared to be highly transient and spatially and temporally variable over short distances across and along the slope (Tohari et al, 2004). Meanwhile, laboratory shear tests under the field stress path have been used to study strength parameters for analysis of the potential for the initiation of rainfall-induced debris flow failures (Sitar and Anderson, 1992; Anderson and Sitar, 1995). The results of these studies suggest that these types of slope failures involve drained initiation along a stress path characterized by decreasing effective stress and nearly constant shear stress.

In Indonesia, understanding of mechanism of rainfall-induced slope failure has been developed based solely on saturated soil mechanics principles that treats the physical process involved in soil drainage and moisture distribution as a “black box”. This is because no direct quantitative measurements of hydrologic responses of volcanic residual soils to rainfall have been performed to evaluate the susceptibility of volcanic residual soil slopes to failure. Thus, direct, physically based methods of evaluating hydrological responses and antecedent soil moisture would greatly improved our understanding of hydrological condition leading to slope failure initiation in volcanic residual soils.

This paper presents the result of a comprehensive research conducted to study the hydrological response of a potential slope failure area to heavy rainfall in order to evaluate the mechanism leading to the initiation of slope failures in volcanic residual soils in West Java. The specific objectives of this study are to (1) obtain field measurement of the hydrological condition leading to slope failure initiation, and (2) assess the significance of the antecedent soil moisture condition to slope failure initiation in volcanic residual soils.

Cadas Pangeran Field Site

The selected research site is located the west corner of a cut-slope portion of the hilly area above the Cadas Pangeran road section (Figure 1). The hilly area in Cadas Pangeran road section, Sumedang regency, West Java is one of the areas highly prone to landslide. On April 4 2005, a slope failure occurred in a natural slope above this road section. Local witnesses revealed that the slope failure was initiated by small failure at the toe of the slope and tension cracking along 100 m along the slope surface.

Figure 1. Cadas Pangeran field site at the Cadas Pangeran cut-slope, Sumedang District, West Java.

To prevent further hazard, the Public Works Division of West Java provincial government had improved the slope by trimming it to 1:1 (H:V) slope and later installed a row of bore piles of diameter 0.6 m at 6.0 m depth at the slope toe. The configuration of stabilisation method is shown in Figure 1. Despite the completion of stabilization works, recent field investigation revealed that cracks were still found along the slope surface, indicating that the slope is still in the critical condition (Figure 2).

Figure 2. Development of cracks on the slope surface (the photograph was taken on April 2006).

METHOD

Site and Soil Characterization

In order to establish the stratification of the slope, mechanical drilling program was conducted at three locations in the study site up to a maximum depth of 22 meters. The location of each drilling borehole is shown in Figure 3. One borehole (DH-01) was located at the upper slope up to the depth of 22.0 m. The other two boreholes (DH-02 and DH-03) were drilled at the lower portions of the slope at the depths of 16.0 and 13.5 m, respectively. The depth of groundwater table was measured following the completion of drilling program.

Disturbed and undisturbed samples recovered from the mechanical drillings were subjected to a series of laboratory tests to determine the index properties, the soil water characteristic (SWC) curves, the permeability and shear strength functions of the soils. The SWC curves were determined using 200 kPa pressure plate extractor (Tohari and Sarah, 2006). Using van Genuchten’s Equation (1980), the SWC curves and the saturated coefficient of permeability, k_s were then used to estimate the unsaturated permeability function, k_w $\{u_a-u_w\}$ required for seepage analysis. The saturated shear strength properties and the SWC curve of the respective soils were used to estimate the unsaturated shear strength function, $\tau(u_a\text{-}u_w)$ using effective stress concept of Khalili and Khabbaz (1998), and shear strength parameters (ϕ^b) for the residual soils required for slope stability analysis were then obtained.

Field Instrumentation

Field instrumentation consisted of jet-fill tensiometers, a tipping bucket rain gauge and a data logging system. Lay-out of the instrumentation is shown in Figure 4.

Jet-fill tensiometer

In total, 24 units of jet-fill tensiometers, each equipped with pressure transducers capable of measuring pore-water pressures from -100 to 200 kPa, were installed in the unstable slope portion at five closely spaced nests (A to E) within 6.0 m radius and to various depths (Fig. 4). Each nest consists of five tensiometers installed at the depths of 0.5, 1.0, 1.5, 2.0 and 3.0 m.

Rain gauge

The research site is equipped with a tipping-bucket rain gauge to obtain site-specific rainfall data (i.e., total and intensity). The rain gauge was calibrated to measure rainfall in increment of 0.2 mm.

Data acquisition system

A smart data logger (ICT Model SL5) is selected for the study. The logger has been programmed to recognize the pressure transducers and rain gauge connected to it and to take readings automatically every 10 minutes. The data were downloaded daily using a remote modem to a personal computer.

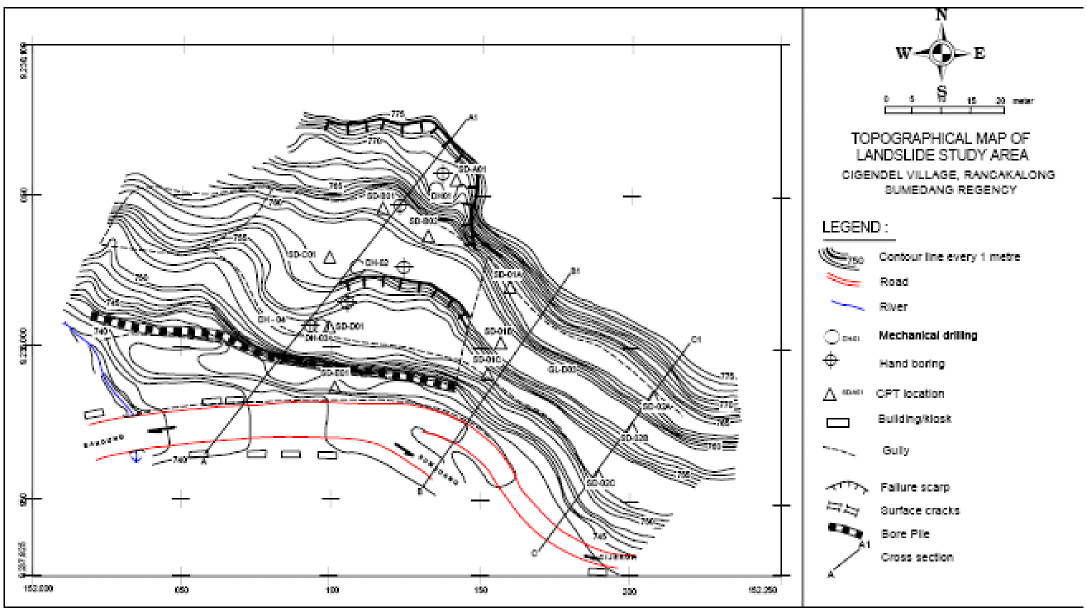

Figure 3. Detailed topographical map of the research site, showing the locations of the subsurface investigation.

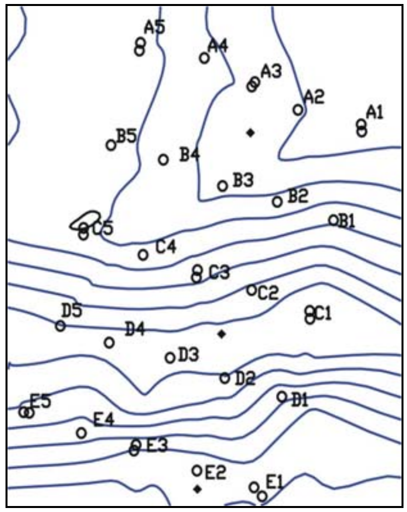

Figure 4. Lay-out of the instrumentation in the research slope.

Seepage Analysis

The seepage analysis was performed using the computer program SEEP/W (Geo-Slope, 2002) to evaluate the effect of antecedent rainfall into the volcanic residual soil on the distribution of transient pore-water pressures within the soil slope.

The initial pore-water pressure distribution within the slope was defined as a hydrostatic pore-water pressure profile with a limiting negative pore-water pressure of 40 kPa. This limit was based on the field measurement at the depth of 3.0 m.

Stability Analysis

The slope stability analysis was performed using the computer program SLOPE/W (Geo-Slope, 2002) to determine the factor of safety for the transient pore-water pressure distribution within the volcanic residual soil slope. The general limit equilibrium (GLE) method was selected as the method of analysis. The time dependent pore-water pressure distribution were used calculate the factor of safety with time.

RESULTS OF INVESTIGATION

Soil Stratification

The results of the field geotechnical investigations showed that the slope is composed of three layers of soils originated from volcanic tuff and breccia of approximately 28 meters thick. The stratification of the slope is divided into four different layers (Figure 5) as the following:

1. Reddish brown silty clay of 3.0 – 4.0 m thick with N-SPT value of 13-22. This layer represents the complete form of fully weathered tuff (weathering grade V-VI).

2. Brown loose fine silty sand layer of 2.0 – 6.5 m thick, N-SPT value of 5-10 and cone resistance values, q_c of 21-35 kg/cm^2. Andesite fragments of gravel to pebble sizes are found in this stratum. This layer is characterised as the moderate to high weathering of volcanic breccia (weathering grade IV-V).

3. Yellowish brown dense fine sand layer containing andesitic gravels, derived from highly weathered volcanic breccia (grade III-IV) with varying thickness of 4.0 – 10.0 m. N-SPT value of this layer is 11- 28 and the cone resistance value q_c of 40 -120 kg/cm^2.

4. Grey volcanic breccia, fresh to weakly weathered (grade I-II) with values of N-SPT >30.

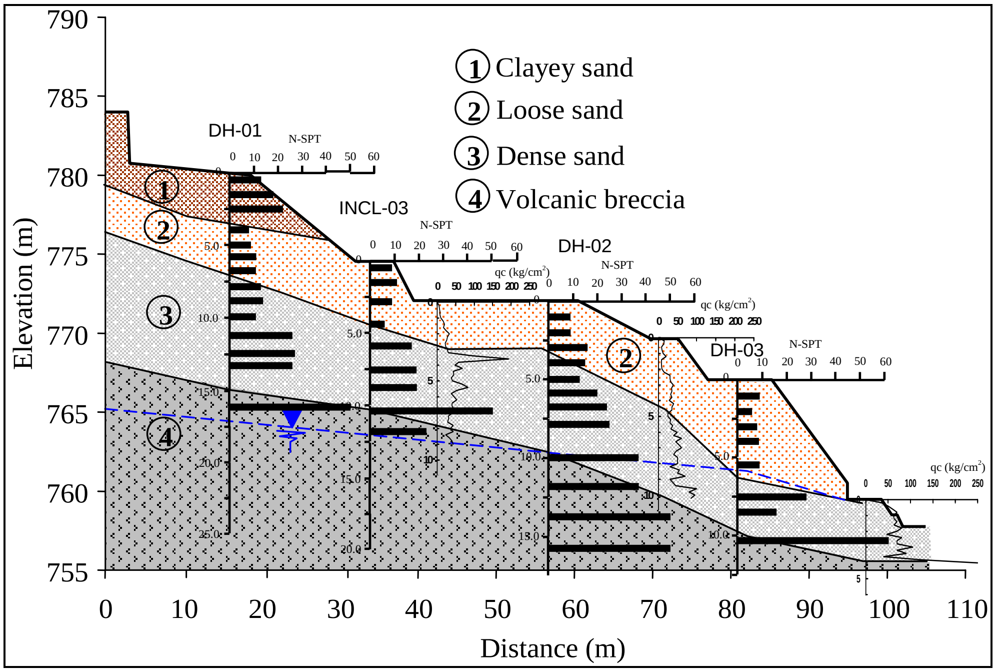

Figure 5. Cross section of Cadas Pangeran landslide along line A-A', illustrating the soil stratification and the values of N-SPT and tip resistance (q_c) at each drilling location.

Groundwater Table

The results of measurement (Table 1) indicate that the groundwater table becomes shallower towards the slope toe. At the slope toe, the groundwater table presents within the loose sand layer.

Table 1. Depth of groundwater table.

Bore No.	Borehole depth (m)	Depth of groundwater table (m)	Aquifer layer
DH-01	22,0	16,8	Dense fine sand
DH-02	16,0	9,9	Dense fine sand
DH-03	13,5	4,7	Loose silty sand

Soil Characteristics

Table 2 shows the summary of the index, hydraulic and shear strength properties of the soils obtained from the laboratory tests. The results of direct shear tests on undisturbed samples obtained from the research slope showed that the cohesion of clayey silts and sand layers was 19.0 and 33.0 kPa, respectively. Meanwhile, the angle of internal friction of the respective soils was 30.0^o and 32.0^o. Meanwhile, according Tohari et al (2006), the loose silty sand appeared to have significantly low cohesion. This is in accordance with the result of N-SPT tests indicating a soft clayey soil layer. Meanwhile, the friction angle of both soils is apparently similar. Thus, the difference in shear strength of the soils was obviously governed by the cohesion.

Table 2. Geotechnical properties of the soils derived from laboratory tests.

Soil Properties	Compact silty clay	Loose silty sand	Dense sand
Plastic limit (%)	50 - 60	50 - 60	20 - 40
Liquid limit (%)	110 - 120	70 - 80	40 -60
Unit weight (kN/m^3)	18.0	17.6	15.1
Saturated coefficient of permeability (m/s)	2.6 x 10^{-6}	1.4 x 10^{-6}	5.1 x 10^{-7}
Porosity	0.614	0.689	0.512
Cohesion (kPa)	19.0	5.0	33.0
Friction angle (^{o})	30.0	20.0	32.0

Soil Water Characteristic (SWC) Curves

Figure 6 shows the SWC curves for each soil layers obtained from the pressure plate experiments. The curves indicate that the soils have an air-entry value (AEV) of approximately 10 kPa, above which the soils start to desaturate. Compared with silty clay soil, the silty sand soil is more easily to desaturate as indicated by a higher effective porosity.

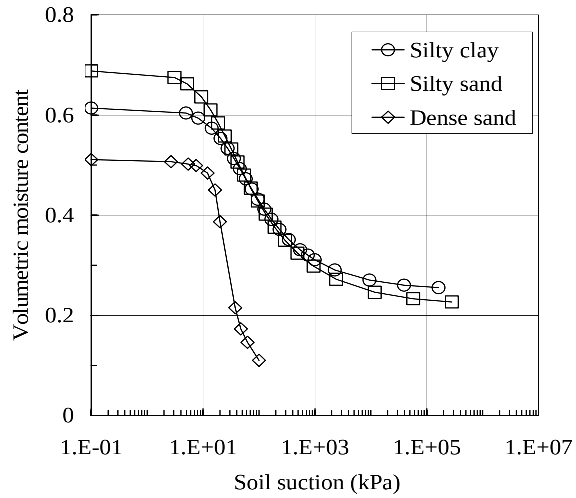

Figure 6. Soil water characteristic curves for each soil type.

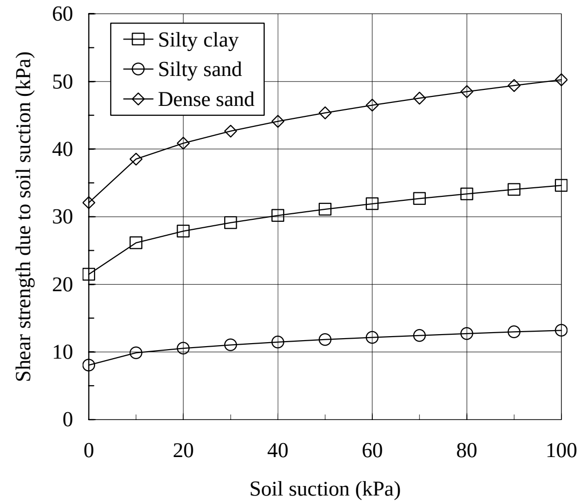

Figure 8. Shear strength functions of each soil type.

Permeability Functions

Figure 7 shows the permeability functions for each soil type. According to this figure, the coefficient of permeability of the soils decreases from the saturated coefficient of permeability when the soil suction becomes greater than 10 kPa. Furthermore, it is also clear that the coefficient of permeability of silty clay is less readily to decrease than that of the sandy silts. Hence, the clayey silt will more easily reach its saturated coefficient of permeability under the effect of rainwater infiltration.

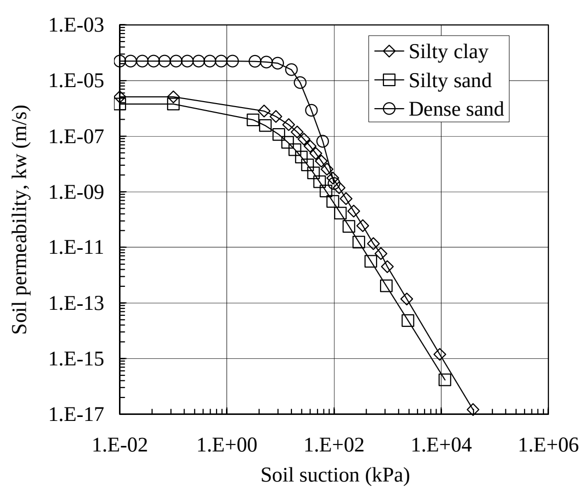

Figure 7. Permeability functions of the soils.

Shear Strength Functions

Figure 8 shows the shear strength functions of each soil layer. From this figure, the value of ϕ^b for each soil was found to be approximately 10^o for soil suction at the air entry value, above which the values of ϕ^b decreasing.

Field Pore-water Pressure Response to Rainfall

One-dimensional plots of pore-water pressure profile recorded during a rainfall period of December 2007 at the research site are given in Figures 9 and 10. A cumulative rainfall of 425 mm with a maximum intensity of 46.3 mm/hr had fallen on the site during this period. Figure 9 shows the typical pore-water pressure profile recorded at the upper most portion of the research slope (i.e. Nest A), while Figure 10 shows the typical pore-water pressure profile recorded at the lower portion of the slope (i.e. Nest D).

The following observations were made regarding the pore-water pressure distribution in the soil slope:

1. Significant negative pore-water pressures can develop during a dry period at the depth of 3.0 meter.

2. Negative pore-water pressures readily dissipate in the upper 3.0 meter with the occurrence of moderate to heavy rainfall event, especially in Nest D. This indicates that rainwater more readily infiltrate into the lower slope portion.

3. The negative pore-water pressures at the depth of 3.0 meter more readily dissipate than that at near surface slope in at Nests A and D. This suggests the existence of a preferential path for moisture movement, such as macro-pores and fractures at the deeper part of soil profile.

4. Perched water table did not form in the upper of 3.0 m of soil during the monitoring period. Thus, long period of heavy rainfall required to

develop positive pore-water pressure within the slope profile.

5. The worst pore-water pressure conditions that can occur in the soil slope is likely to develop at the depth of greater than 2.0 m, especially in the lower portion of the slope. Meanwhile in the upper portion of the slope, the worst case pore-water pressure may develop near the slope surface.

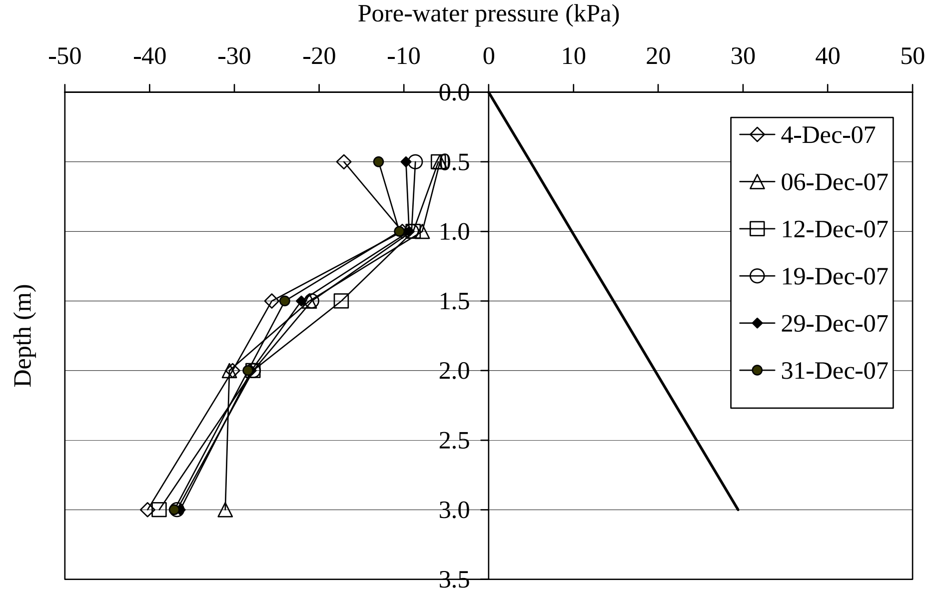

Figure 9. One-dimensional plot of pore-water pressure versus depth for Nest A.

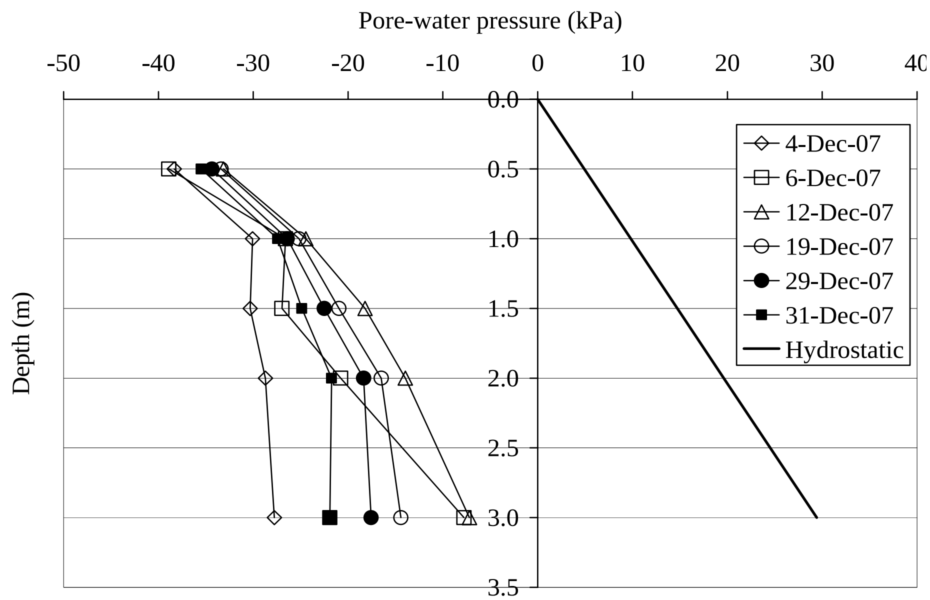

Figure 10. One-dimensional plot of pore-water pressures versus depth for Nest D.

Significance of Antecedent Soil Moisture Condition

The role of antecedent soil moisture conditions is significant to create the worst pore-water pressures. In this study, the soil moisture conditions due to dry antecedent rainfall in October and to wet antecedent rainfall in December 2007 were analyzed to evaluate the significance of the soil antecedent condition in affecting the slope stability.

Figures 11 to 14 show the results of the numerical analyses using SEEP/W and SLOPE/W Program for each antecedent condition. Examining Figure 11, the dry antecedent condition only resulted in the temporary increase of groundwater level near the slope toe. Perched water table seemed to develop at the end of rainfall period as the rainfall intensity increased. As indicated in Figure 12, there are no significant variations of factor of safety of the slope during this period of rainfall.

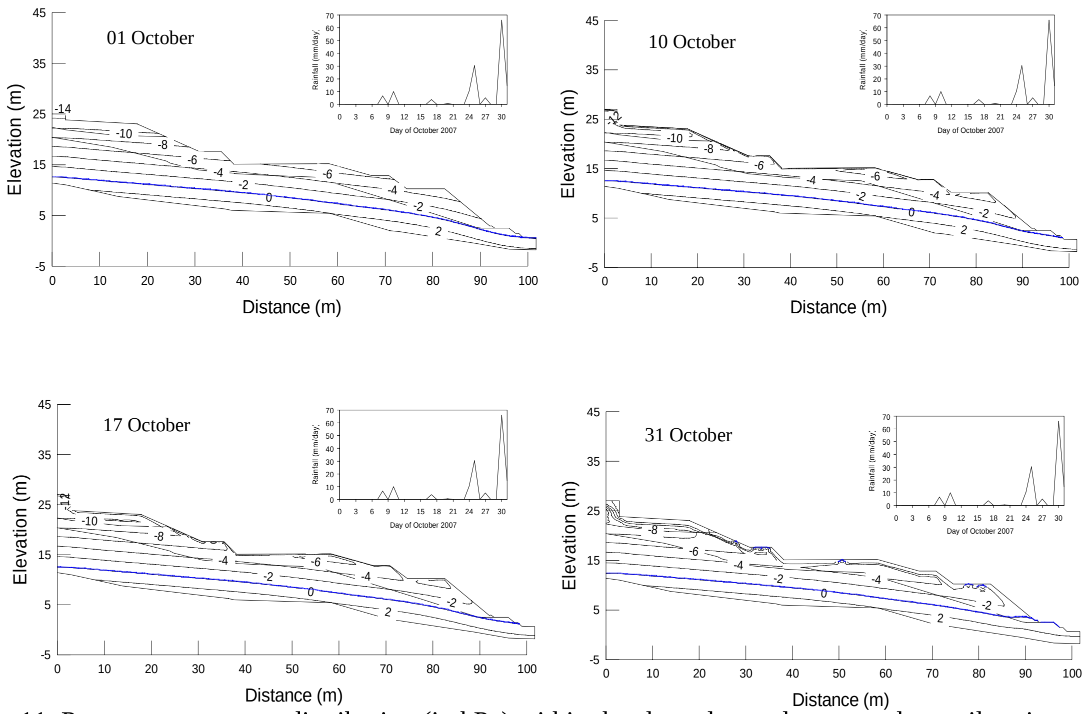

Figure 11. Pore-water pressure distribution (in kPa) within the slope due to dry antecedent soil moisture condition of October 2007.

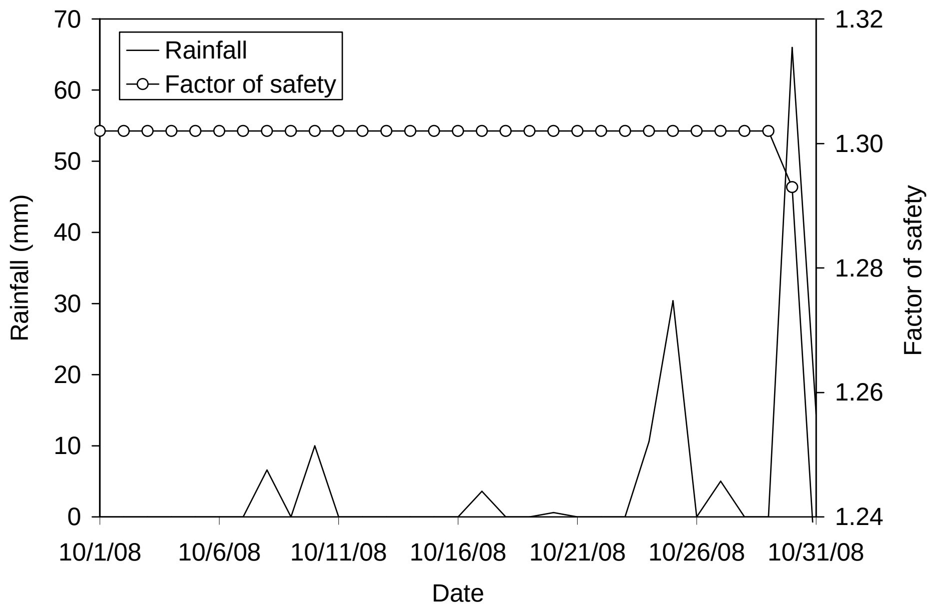

Figure 12. Variation of factor of safety of the slope for dry antecedent soil moisture condition.

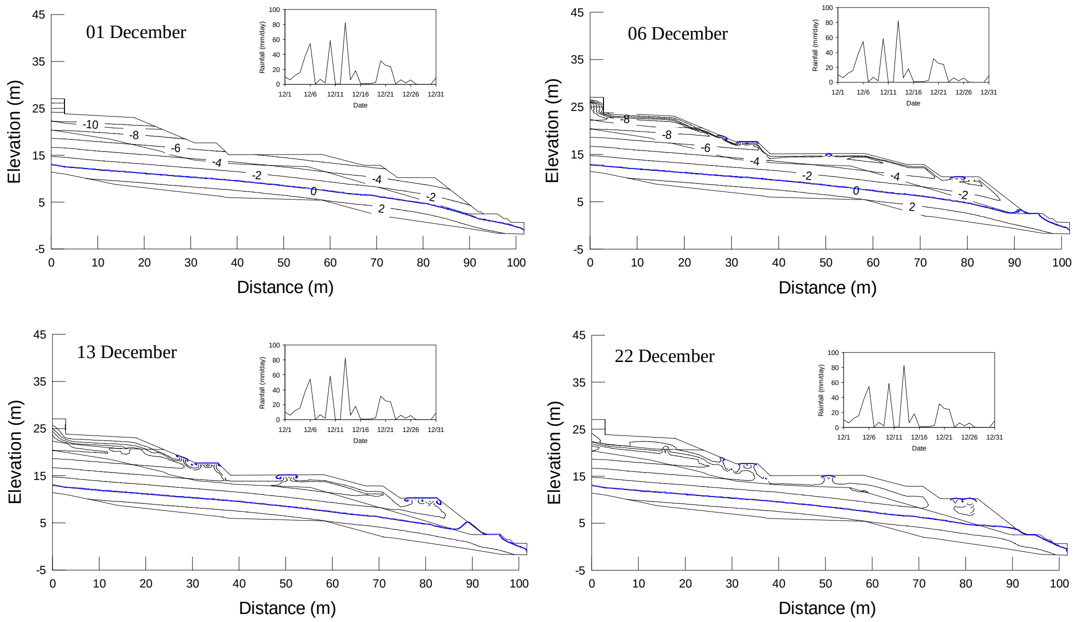

Figure 13. Pore-water pressure distribution (in kPa) within the slope due to wet antecedent soil moisture condition of December 2007.

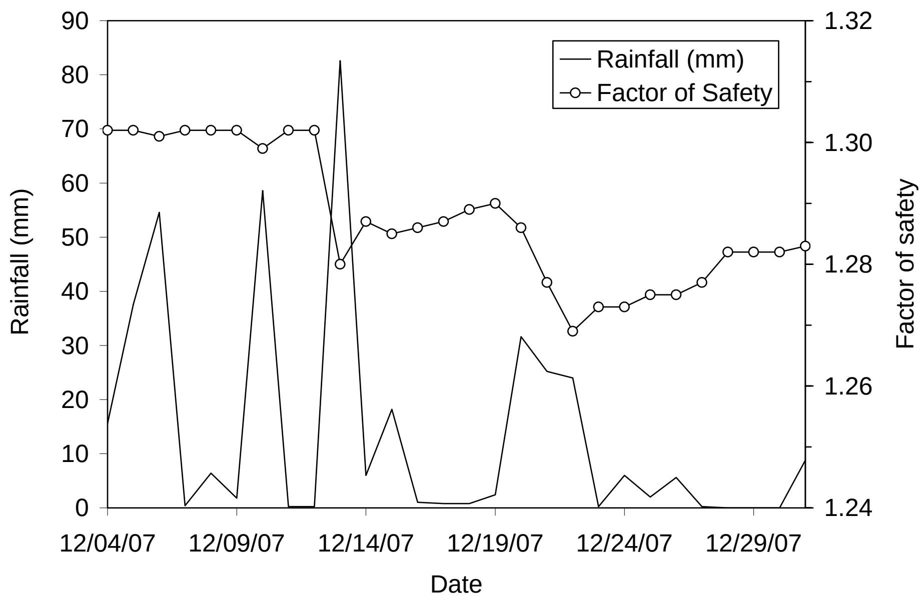

Figure 14. Variation of factor of safety of the slope for wet antecedent soil moisture condition.

In contrast, the wet antecedent condition affected the distribution of pore-water pressures within the slope. Perched water table developed at near surface in most of the rainfall period (Figure 13). Groundwater table increased significantly within the slope, especially at the slope toe. The prolonged increase in groundwater level and the development of perched water table significantly reduced the stability of the slope, as indicated in Figure 14. Rainfall of 80 mm/day would give a significant effect on the stability of the slope.

CONCLUSION

A study of mechanism leading to rainfall-induced slope failure in volcanic residual soil has been carried out in a landslide prone slope in Cadas Pangeran area, Sumedang. Based on the results of this study, the following conclusions are drawn:

Field Hydrological Response to Rainfall

Hydrological response of the soils was spatially and temporally varied with depth. Generally, pore-water pressures within the slopes decrease as the depth increases. The greater pore-water pressure exists at the depth of 3.0 meters.

The movement of the wetting front is likely to be confined to in the upper 2 m of the soil. However, at the greater depth, a preferential path for moisture movement may exist to contribute the generation of pore-water pressures.

Rainfall of high intensity and short duration is likely to produce a perched water table within the near surface soil layer. But, a long period of rainfall may be necessary to produce the hydrological condition leading to landslide initiation.

Antecedent Soil Moisture Condition

Dry antecedent soil moisture condition will require rainfall of high intensity to saturate the soil profile and to disturb the stability of the slope. Under wet antecedent soil moisture condition, rainfall of 80 mm/day is likely to produce the hydrologic condition leading to slope instability.

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